

NASA TECHNICAL
MEMORANDUM

NASA TM X-53399

February 23, 1966

NASA TM X-53399

| | | |
|-------------------|-------------------------------|------------|
| FACILITY FORM 602 | N66-22928 | |
| | (ACCESSION NUMBER) | (THRU) |
| | 38 | / |
| | (PAGES) | (CODE) |
| | TMX-53399 | 30 |
| | (NASA CR OR TMX OR AD NUMBER) | (CATEGORY) |

THE LUNAR ATMOSPHERE

By Wilmuth C. Lucas^{*} and Otha H. Vaughan, Jr.
Aero-Astroynamics Laboratory

*Northrop Space Laboratories

NASA

*George C. Marshall
Space Flight Center,
Huntsville, Alabama*

GPO PRICE \$ _____

CFSTI PRICE(S) \$ _____

Hard copy (HC) 2.06

Microfiche (MF) 1.50

653 July 65

TECHNICAL MEMORANDUM X-53399

THE LUNAR ATMOSPHERE

by

Wilmuth C. Lucas* and Otha H. Vaughan, Jr.

George C. Marshall Space Flight Center

Huntsville, Alabama

ABSTRACT

N66-22928

A survey of the state of the art of lunar atmospheric models is presented. Based on the results of this survey, the authors conclude that the lunar atmosphere is extremely complex and that its composition and density probably vary locally and are influenced by volcanic, meteoritic, and solar activity. The major components of the atmosphere will probably be H_2 , H_2O , Ar, He, Kr, and Xe.

An engineering lunar atmospheric model (ELAM) is described.

Author

*Northrop Space Laboratories, Huntsville, Alabama

NASA - GEORGE C. MARSHALL SPACE FLIGHT CENTER

TECHNICAL MEMORANDUM X-53399

February 23, 1966

THE LUNAR ATMOSPHERE

by

Wilmuth C. Lucas and Otha H. Vaughan, Jr.

Aero Space Environment Office
Aero-Astroynamics Laboratory

ACKNOWLEDGEMENTS

The authors wish to express appreciation to Mr. James T. Stanley and Mr. Robert Bensko, Systems Section, Northrop Space Laboratories for their individual aid and consultation during the preparation of this report.

TABLE OF CONTENTS

| | <u>Page</u> |
|--|-------------|
| I. INTRODUCTION..... | 1 |
| II. OPTICAL AND RADIO OBSERVATIONS..... | 2 |
| A. Stellar Occultations..... | 2 |
| B. Spectroscopic Methods..... | 4 |
| C. Brightness and Polarization of Scattered Light..... | 4 |
| D. Radio Observations..... | 5 |
| III. LUNAR ATMOSPHERE SOURCES..... | 5 |
| A. Primitive Atmosphere..... | 5 |
| B. Solar Wind..... | 6 |
| C. Decay Products from Radioactive Elements..... | 8 |
| D. Outgassing and Meteoritic Volatilization..... | 9 |
| E. Volcanism..... | 10 |
| F. Miscellaneous Sources..... | 13 |
| IV. ESCAPE MECHANISMS..... | 14 |
| A. Thermal Escape..... | 14 |
| B. Solar Wind Scattering..... | 17 |
| C. Ionic Escape..... | 18 |
| V. DEVELOPMENT OF A SYNTHESIZED LUNAR ATMOSPHERIC MODEL..... | 19 |
| VI. CONCLUSIONS..... | 20 |

LIST OF TABLES

| <u>Table</u> | <u>Title</u> | <u>Page</u> |
|--------------|--|-------------|
| 1 | Lunar Atmosphere Observation..... | 3 |
| 2 | Surface Densities of Gases Accreted from the Solar Wind..... | 7 |
| 3 | Ion Densities at Lunar Surface for Various Models. | 7 |
| 4 | Contents of the Fissured Surface Materials Models. | 8 |
| 5 | Composition and Percentage of Gases from Selected Igneous Rocks..... | 10 |
| 6 | Observations of Possible Lunar Volcanic Activity.. | 11 |
| 7 | Thermal Velocities of Volcanic Emanations and Sublime Vapors at Subsolar and Molten Lava Tem- peratures..... | 15 |

TECHNICAL MEMORANDUM X-53399

THE LUNAR ATMOSPHERE

SUMMARY

An attempt was made to synthesize the most probable model of the lunar ambient atmosphere derived from available reports and professional papers. Various observation methods and their results were reviewed. The different theoretical approaches to the problems of defining lunar atmosphere sources, source rates, escape mechanisms, and escape rates were critically studied. It was concluded that the lunar atmosphere is extremely complex, and that its composition and density probably vary locally and are influenced by volcanic, meteoritic, and solar activity.

The lunar atmosphere is assumed to have a density greater than the density of the interplanetary medium but less than 10^{-13} of the earth's atmosphere at sea level. The major components of the atmosphere probably will be H_2 , H_2O , Ar, He, Kr, and Xe.

An accurate evaluation of the lunar atmosphere must await the data obtained from future lunar missions; however, a lunar atmospheric model is presented for use as design criteria.

This report was prepared under NASA Contract NAS8-20082.

I. INTRODUCTION

Present knowledge of the lunar atmosphere is limited to estimates based on earth-based optical and radio observations, and on theoretical approaches. From recent observations, it has been determined that the upper limits of the lunar atmosphere are approximately 10^{-13} of the terrestrial atmosphere. Theoretical approaches indicate that this figure may be too high.

For most purposes this tenuous atmosphere would have little effect on lunar missions. However, there are a few areas where detailed knowledge of the atmosphere would be important. As noted by Öpik [1], even a medium as tenuous as this would influence the charge of the lunar surface and possibly the behavior of lunar surface dust particles, and would be sufficient to absorb some spectral line emissions. The characteristics of the lunar atmosphere also would be of geologic interest, because they could reflect the weathering and aging processes present on

the moon. Additional areas pointed out by Green [2] were radon and argon generation from crustal rocks, detection of meteorite flashes, significance of the coloration of crater rays, and possible transient local atmospheres of volcanic origin. In addition, knowledge of the atmosphere would be of great value in determining the origin of the moon.

The objective of this document is to establish the most likely lunar atmospheric model by objectively considering all the hypotheses and available facts. This model should be useful in establishing design criteria for future lunar missions.

II. OPTICAL AND RADIO OBSERVATIONS

From prehistoric times the moon has aroused the curiosity of man, but not until Galileo were critical observations made. In approaching the problem of the existence of a lunar atmosphere, man naturally compared it with his own terrestrial environment. It was assumed that the vast, seemingly smooth areas were seas and that the lunar atmosphere was similar to the earth's. In 1753, Roger Boscovich (cited in Ref. 3) concluded that the lunar atmosphere's density was either extremely low or nonexistent. It was the twentieth century before these observations were definitely confirmed (Table 1).

A. Stellar Occultations

Some of the early efforts to determine the density of the lunar atmosphere were attempted by optical observations of stellar occultations. Two effects are noted during a stellar occultation: horizontal refraction and photometric dimming.

If an appreciable amount of atmosphere were present on the moon, the effects of horizontal refraction would be detected. During occultation, the star would be shifted above the lunar limb by an angle equal to the angle of refraction, thus decreasing the duration of the occultation. This would appear, when compared with direct measurement, as an apparent decrease of the angular radius of the limb. To date, this phenomenon has not been observed. Therefore, Öpik [1] concluded that the upper limit of observable horizontal refraction is $n - 1 < 1.62 \times 10^{-7}$, which is proportional to an atmospheric density of $< 5.5 \times 10^{-4}$ of the earth's.

Photometric dimming effects are caused by Rayleigh scattering and horizontal refraction functioning as a negative lens. As shown by Öpik [1], Rayleigh scattering will cause only 0.1 percent to be absorbed

TABLE 1
LUNAR ATMOSPHERE OBSERVATIONS

| Investigator(s) | Observation Method | Maximum Density in Terrestrial Atmospheres |
|--|--|--|
| Russel, Dugan, and Stewart (1926) | Absence of Twilight | $< 10^{-4}$ |
| Fesenkov (1943) | Surface Brightness | $< 10^{-6}$ |
| Lyot & Dollfus (1949) | Photography of twilight in yellow light, with a 20 cm coronagraph | $< 10^{-8}$ |
| Dollfus (1952) | Photograph of twilight in orange light, with a 20 cm coronagraph and Savart- Lyot solariscope | $< 10^{-9}$ |
| Lipski (1953) | Photography of twilight in green light, with a polarimeter | $< 10^{-4}$ |
| Ellsmore & Whitfield (1955) | Occultation of radio stars by the moon | $< 10^{-12}$ |
| Costain, Elsmore & Whitfield (1956) | Refraction of radio waves in the lunar ionosphere | $< 10^{-13}$ |
| Elsmore (1957) | Refraction of signals from radio star sources during lunar occultations | 2×10^{-13} |
| Öpik (1962) | Twilight Arc | $< 10^{-8}$ |
| Hazard (1963) | Refraction of signals from radio star sources during lunar occultations | 2×10^{-13} |

with a pure atmosphere of a density $< 5.5 \times 10^{-4}$ of the terrestrial atmospheric density. This value is undetectable. He also noted that light dimming due to horizontal refraction is the more important of the two causes; however, even this method is not sensitive. Comparing horizontal refraction and photometric dimming, we see that horizontal refraction is definitely a more sensitive criterion.

B. Spectroscopic Methods

The use of spectroscopic analysis for detecting lunar atmosphere was first considered by Jannsen [4] in 1863. Both luminescence spectrum and absorption spectrum methods have been used. Recent studies (cited in Ref. 3), notably Keyper's searching for sulphur dioxide using the luminescence spectrum method, and Herzberg's and Kozyrev's searching the darker portions of the moon for emission bands using the absorption spectrum methods, have failed to detect a lunar atmosphere.

C. Brightness and Polarization of Scattered Light

Observations of the brightness and polarization of scattered light for estimating the density of the lunar atmosphere are the most sensitive of the optical methods.

Because the brightness of the lunar surface would overshadow the scattering effect of light in the tenuous atmosphere, observations are made only on the unilluminated part of the moon in an effort to detect the twilight phenomenon.

As noted by Russell (cited in Ref. 3), if the density of the lunar atmosphere was $< 10^{-5}$ of the terrestrial, the twilight phenomenon would be optically visible. This illumination should be the greatest near the cusps. The extension of the cusps into the dark area of the moon is referred to as the twilight arc. Öpik [5] developed Russell's conclusions, but his observation failed to detect an atmosphere. He deduced from this failure that the atmosphere was less than 10^{-8} of the earth's.

To offset interference caused by earthshine, aureale, and internal light scattering in the telescope, polarization methods were introduced. In 1943, Fesenkov (cited in Ref. 3), using a polarization method, did not detect any variations in the brightness during observations of the lunar terminator. Dollfus [6] performed extensive observations from Pic du Midi using polarization methods, but was unsuccessful in detecting any trace of polarization. Because of the accuracy of his measurements, it was possible to reduce the maximum limit for the density of the lunar atmosphere to 10^{-9} of the terrestrial.

D. Radio Observations

Observation of radio occultations has proven to be the most sensitive of the methods used in attempting to determine the density of the lunar atmosphere. This method is based on the fact that radio waves from a radio star during occultation will be refracted in the ionized gas on the sunlit side of the moon. The length of the eclipse is accurately determined and compared with a calculated value. The electron density of the lunar atmosphere will cause refraction of the radio waves, thus accounting for any differences between observed and calculated values. From these differences estimates of the density of the atmosphere can be calculated.

Elsmore and Whitfield [7] were leaders in the use of radio occultations for this purpose. In 1955, using a radio star 2C 537 of Nebular IC 443, they made their first observation. The results of this observation led to the conclusion that the lunar atmosphere was 10^{-12} as dense as the earth's. Later observations by Costain, Elsmore, and Whitfield (cited in Ref. 8), Elsmore [9], Hazard Mackey and Shimmins [10] reduced this value to approximately 10^{-13} of the terrestrial atmosphere.

III. LUNAR ATMOSPHERE SOURCES

With the limited knowledge available concerning the lunar surface and, in general, the geology of the moon, only speculative conclusions can be made as to the present and past sources of a lunar atmosphere. Innumerable lunar surface composition models and atmosphere-producing processes have been formulated and with each, its own unique atmosphere. The notable theories are discussed in the following paragraphs.

A. Primitive Atmosphere

The existence of remnants of an ancient lunar atmosphere composing part of the present lunar atmosphere seems unlikely.

The origin of the moon and the earth is unknown, but it is probable that they were formed under similar conditions. It follows that the formation of lunar and terrestrial atmospheres also would be similar. There are two major categories under which hypotheses concerning the origin of the present terrestrial atmospheres can be grouped. One of these is that the atmosphere is a residual of an original atmosphere present when the moon was in a molten state, and the other is that the atmosphere was developed by leakage from within.

Two models have been proposed for the primitive atmosphere: one composed of CH_4 and NH_3 and the other of CO_2 and N_2 . As noted by Rubey [11], the quantities of excess volatiles in the earth's atmosphere and hydrosphere, and the equilibrium constants for reactions of CH_4 and NH_3 and other gases indicate that CO_2 and N_2 were more likely to have composed the primitive atmosphere. However, chemical effects that would have been produced by a dense CO_2 and N_2 atmosphere have not been discovered by geologic investigations. Because of this, Rubey concluded that the accumulation of gases by the gradual escape of water vapor, CO_2 , CO , N_2 and other volatiles during geologic times seems a more likely explanation of the earth's atmosphere. It is probable that this is also true for the moon.

Even if the concept of a primitive atmosphere of CH_4 and NH_3 , or CO_2 and N_2 is accepted, the moon with its low escape velocity and active escape mechanisms, thus its high loss rate, probably could not have held the atmosphere for this period of time.

B. Solar Wind

The bombardment of the lunar surface by solar wind protons was suggested by Gold [12] as a source of hydrogen. Hinton and Taeusch [13] recognized the solar wind as a source of neutral hydrogen and helium. They assumed that every positively charged solar wind particle which impinges the lunar surface is confined and then re-emitted as a neutral atom. Herring and Licht [14] calculated the density of monatomic hydrogen based on a proton flux of $10^{10} \text{ cm}^{-2}\text{sec}^{-1}$ to be $3.9 \times 10^4 \text{ atoms cm}^{-3}$. Öpik [1] generally agrees with Herring and Licht, except for concluding that H_2 , rather than H , would be present and for a slight difference in calculated densities. Öpik derived a particle density of $1.2 \times 10^4 \text{ particles cm}^{-3}$.

The possibility that the solar wind contains heavier elements was studied by Nakada and Mihalov (cited in Ref. 15). Considering the solar wind proton scattering loss mechanism and electrostatic loss mechanism, they concluded a lunar model atmosphere would contain oxygen, nitrogen, neon, and argon.

That most of the estimates concerning the solar wind as a source have been based on a maximal accretion rate was pointed out by Michel [16]. Using a different solar wind model he calculated $S \approx 40 \text{ g-sec}$. Moreover, he determined that the source strength due to the heavy ion components would be $S \approx 0.4 \text{ g-sec}$.

However, he concluded that the solar wind is not a major contribution to the lunar atmosphere in the normal sense because ionized hydrogen and helium, which are the major constituents of the solar wind, are weakly bound to the lunar surface. He qualified this conclusion only if contributions from other sources were much lower than have been estimated.

TABLE 2

SURFACE DENSITIES OF GASES ACCRETED FROM THE SOLAR WIND
(Bernstein, Fredricks, Vogl, and Fowler, The Lunar Atmosphere
and The Solar Wind, Icarus, Volume 2, p. 240, 1963)

| MODEL | Ne | A ³⁶ | Kr | N | H |
|------------------------|--------------------|--------------------|-----------------------|-----------------|-----------------|
| Abundance per hydrogen | 5×10^{-4} | 8×10^{-6} | 10^{-8} | 10^{-4} | -- |
| Thermal Escape Alone* | 3×10^7 | 2×10^{12} | 2×10^{11} ** | 5×10^4 | 3×10^3 |
| Solar Wind Scattering* | 1.5×10^6 | 5×10^4 | 10^2 | 5×10^4 | 3×10^3 |
| Total Escape of Ions* | 10^5 | 10^3 | 0.5 | 10^4 | 3×10^3 |

*NV = 10^9 protons $\text{cm}^{-2}\text{sec}^{-1}$

**Limited by age of moon, assumed 4×10^9 years

TABLE 3

ION DENSITIES AT LUNAR SURFACE FOR VARIOUS MODELS
(Bernstein, Fredricks, Vogl, and Fowler, The Lunar Atmosphere
and The Solar Wind, Icarus, Volume 2, p. 240, 1963)

| MODEL | Ne | A ⁴⁰ | A ³⁶ | Kr | N | H | Total |
|-------------------------|-----------------|-------------------|-----------------|-----------------|--------|--------|-----------------|
| Thermal Escape Alone* | 10^4 | 8×10^9 | 10^9 | 5×10^8 | 25 | 10 | 10^{10} |
| Solar Wind Scattering* | 6×10^2 | 1.5×10^2 | 30 | 0.3 | 25 | 10 | 9×10^2 |
| Solar Wind Scattering** | 6×10^3 | 1.5×10^2 | 3×10^2 | 1 | 10^3 | 10^3 | 8×10^3 |
| Total Escape of Ions** | 40 | 1.5 | 0.6 | 10^{-3} | 5 | 10 | 56 |
| Total Escape of Ions** | 4×10^2 | 1.5 | 6 | 10^{-2} | 50 | 10^3 | 10^3 |

*NV = 10^9 protons $\text{cm}^{-2}\text{sec}^{-1}$

**NV = 10^{10} protons $\text{cm}^{-2}\text{sec}^{-1}$

Bernstein et al. [15] calculated lunar atmosphere models for various solar wind regimes. These are shown in Tables 2 and 3.

C. Decay Products from Radioactive Elements

The decay of radioactive elements would be a source of argon, krypton, radon, thoron, and xenon. The amount and variety of gas would vary with the composition of the lunar surface. Krypton and xenon are produced by the spontaneous fission of U^{238} and the decay of I^{129} , while the decay of K^{40} produces argon. Uranium, through the decay of radium, would produce radon, while thorium would yield thoron.

In considering decay products from radioactive elements as a lunar atmosphere source, Green [2] considered three models of fissured surface material. These are that (1) the maria consist of basalt, (2) the highlands consist of rhyolitic material, and (3) the lunar surface is composed of chondritic materials. Table 4 shows the possible quantities of uranium, thorium, and potassium present in the different models as stated by Green.

TABLE 4
CONTENTS OF THE FISSURED SURFACE MATERIALS MODELS

| Element | Maria (Basalt) | Highlands (Rhyolitic) | Chondritic |
|-----------|----------------|-----------------------|------------|
| Uranium | 0.5 ppm | 4 ppm | 100 ppm |
| Thorium | 3 ppm | 20 ppm | 200 ppm |
| Potassium | 5,000 ppm | 40,000 ppm | 850 ppm |

From Table 4 it can easily be seen that potassium would be the major source of an atmosphere derived from the decay of radioactive elements. Vestine [17] calculated that over a period of 3×10^9 years, 4.0×10^{22} molecules would be produced per square centimeter of the lunar surface. To arrive at this figure, it was necessary to assume that:

- (1) Potassium composes 0.12 percent by weight of the moon.
- (2) Potassium 40 makes up 0.011 percent of the total potassium content.
- (3) Each gram of K^{40} produces 0.1 grams of Ar.

Additional calculations by Hinton and Taeusch [13] set the source strength of argon at the surface on 1.9×10^5 atoms per cm^2sec .

Because of the relatively short half-lives of I^{129} , U^{238} , and thorium, their importance as present sources of a lunar atmosphere is negligible. However, in the past, they probably contributed krypton, xenon, radon, and thoron to earlier lunar atmospheres. Bernstein et al. [15] calculated that the decay of I^{129} since the creation of the moon would yield in surface densities 10^{10} xenon atoms per cm^{-3} if loss mechanisms were neglected.

D. Outgassing and Meteoritic Volatilization

Outgassing as used here refers to the releasing of occluded gases from the lunar surface. During the early history of the moon, outgassing was probably a major contributor to the lunar atmosphere. The present rate of outgassing is assumed to be low except where fresh material has been exposed by meteorites, landslides, exfoliation of rocks, and other phenomena.

.. In considering outgassing of the lunar surface as an atmosphere source, Opik [1] estimated a source strength of $< 6 \times 10^4$ CO_2 molecules per cm^2sec . This was based on the deduction that the lunar activity was less than one-thousandth of the earth's. In determining the source strength for the earth, it was estimated that an average of 1 km^3 of igneous rock is outgassed annually and that the gas proportions were the same as for meteorites.

The use of exposed terrestrial igneous rock with the gas proportions of meteorites seems inconsistent. A more logical approach, even though there is the question of atmospheric contamination, would be to consider the gas proportions of a number of reasonable models such as basaltic, rhyolitic, chondritic, etc., or combinations of these. Even with this approach, however, the chances of obtaining accurate values are extremely low. Shepherd [18], in his work on magmatic gases, pointed out that the distribution of volatiles in rocks and lavas is largely fortuitous. Table 5, compiled from Shepherd's data concerning gases from rocks in vacuo, shows the abundance of gas varieties for a number of rock types.

Sytinskaya (cited in Ref. 19) has theorized meteoritic impact as a source of xenon and krypton. She calculates an atmosphere composed of 95 percent xenon and 5 percent krypton with a density of about 10^{-13} atmospheres. The past and present mass rates of meteorites striking the surface are unknown. Because of the lack of knowledge in the areas of lunar geology and lunar environment, accurate values for the past and present rates of outgassing are impossible to calculate.

TABLE 5

COMPOSITION AND PERCENTAGE OF GASES FROM SELECTED IGNEOUS ROCKS

| | Obsidians (Rhyolitic) | Andesitic Lavas | Basaltic Lavas | Plutonic Rocks |
|------------------|--------------------------|--------------------|-------------------|-------------------|
| CO ₂ | 0.666 | 6.557 | 9.079 | 6.436 |
| CO | 0.143 | 0.972 | 1.575 | 0.616 |
| H ₂ | 0.581 | 0.413 | 1.997 | 7.190 |
| N ₂ | 1.593 | 0.985 | 2.4.4 | 1.171 |
| A | Trace | 0.007 | 0.012 | 0.009 |
| S ₂ | 0.070 | 1.028 | 1.084 | 1.186 |
| Cl ₂ | 1.427 | 1.905 | 0.572 | 0.286 |
| F ₂ | 3.190 | 1.770 | 4.928 | 1.220 |
| H ₂ O | 92.327 | 86.348 | 78.275 | 81.831 |

E. Volcanism

Estimates of source strengths of possible gas varieties from volcanic sources are extremely speculative. That volcanism has been a source in the past can be assumed with a degree of confidence. Volcanic features appear to be evident over large areas of the lunar surface. However, volcanism as a modern lunar atmosphere source has not been established. Over the past one hundred and thirty years a large number of observations have indicated that volcanism may still be continuing on the lunar surface, but verification of these phenomena as solely volcanic has been unsuccessful. A complete summary of observations was compiled by Green [20]. Table 6 lists some of the more interesting phenomena observed.

TABLE 6
OBSERVATIONS OF POSSIBLE LUNAR VOLCANIC ACTIVITY

| DATE OF OBSERVATION | LUNAR FEATURE | NATURE OF CHANGE | OBSERVER(S) |
|------------------------------|---|--|--|
| 1963 | Aristarchus (including Cobrahead) | Reddish orange color change with "sparkle" in some areas | Greenacre E. Barr F. Dugan J. Hall D. Jacobs |
| 19 Nov. 1958 19 Dec. 1958 | Alphonsus | Reddish patch close to central mountain | H. Wilkins |
| 18 Nov. 1958 | Alphonsus | Diffuse cloud over central mountain | F. Poppendiek W. Bond |
| 3 Nov. 1958 | Alphonsus | Reddish glow followed by efflux of gas | N. Kozyrev |
| 26 Oct. 1956 | Alphonsus | Differences in detail in infrared versus ultra-violet photo- graphs | D. Alter |
| ca. 1955 | Agarum Promontory | Mist-like appearance | H. Wilkins P. Moore |
| 1933-53 | Timocharis | Frequent mists within crater | D. Barcroft |
| 4 Apr. 1952 | Plato | Obscuration of floor | T. Cragg |
| 20 Aug. 1951 | Pickering | Brilliant white patch within crater | P. Moore |
| 17 May 1951 | Gassendi | Bright speck of short duration | H. Wilkins |
| 1951 | Linne | Morphological change | F. Thornton |
| 8 Aug. 1948 | Earthlit portion of the moon | Bright flash | A. Woodward |

TABLE 6 (Continued)

| DATE OF OBSERVATION | LUNAR FEATURE | NATURE OF CHANGE | OBSERVER(S) |
|----------------------------------|--------------------------------|---|--------------------------------------|
| 9 Oct. 1945 | Plato | Bright flash on floor near west wall | F. Thornton |
| 1939 and 31 Aug. 1944 | Schickard | Dense fog in 1939, mist on floor in 1944 | P. Moore and H. P. Wilkins |
| 1939 | Copernicus | Faint glow lasting 15 minutes | H. P. Wilkins |
| 26 Oct. 1937 | Alphonsus | Milky floor of Alphonsus as well as of Ptolemageus and Herschel | D. Alter |
| 10 Feb. 1919 | Schroter's Valley Cobrahead | Pronounced vapor column | F. H. Thornton |
| Jan-May 1914 | Eimmart | Spreading apron of white material on north interior slope | W. H. Pickering |
| ca. 1905 | Apennine Mountains | Variable spots | W. H. Pickering |
| 1902 | Thaetetus | Nearby white cloud | M. Charbonneau |
| 1869-97 and 2 Oct. 1904 | Plato | Total or partial obscuration of floor | T. G. Elger, H. J. Klei and R. Hodge |
| 1893 | Schroter's Valley Cobrahead | Puff of whitish vapor obscuring details | W. H. Pickering |
| 27 Mar. 1882 | Plato | Milky appearance of floor; one hour duration | A. S. Williams |
| 1870-80 | Tycho | Mistiness | W. R. Birt |
| 1869-71 | Plato | Visible changes in appearance over several decades | T. G. Egler |
| 1840-1843, Oct.-Nov. 1866 & 1867 | Linne | Disappearance of crater in 1866 | J. Schmidt |

This apparent lack of volcanic activity has been pointed out by some authorities as evidence that lunar volcanism has become extinct. This may not be the case if the moon's volcanic history is similar to the earth's. Throughout geologic time the earth has cycled between quiet and active volcanic periods. The possibility that the moon is in a quiet period may explain this apparent lack of volcanic activity. There is also the possibility that many volcanic emissions may go undetected.

To determine a model for lunar volcanism, it is natural that many authors have turned to the earth as an analogue. Difficulties arise, however, when one considers that the cause and mechanism of terrestrial volcanic eruptions, and the reasons for the variations in terrestrial volcanic material, have not been fully answered.

Because of work by Shepherd [18], Jaggar [25], and Naughton and Terada [26] concerning the composition of Hawaiian magmatic gases, Eaton and Murata [21] were able to establish a typical composition. A typical composition in volume percent is listed as follows: H_2O , 79.31; CO_2 , 11.61; SO_2 , 6.48; N_2 , 1.29; H_2 , 0.58; CO , 0.37; S_2 , 0.24; Cl_2 , 0.05; A , 0.04. However, these values may vary over a wide range for individual samples, and the amount of N_2 and the degree of oxidation present may be the result of atmospheric contamination. A more detailed listing of volcanic products is shown in Section IV.

Investigations of gas emanations from thermal springs in Lassen and Yellowstone National Parks have indicated an abundance of helium, neon, argon, krypton, and xenon. Using the isotope dilution procedure, Mazor and Wasserburg [22] concluded from their study that argon, neon, krypton, and xenon originated from the atmosphere through dissolution in ground water. They contributed the excess abundance of helium to juvenile helium from radioactive decay.

From the knowledge acquired from investigations of magmatic gases by volcanologists, it can be assumed that the major constituents of lunar volcanic emissions have been H_2O , CO_2 , and SO_2 .

F. Miscellaneous Sources

A number of possible lunar atmosphere sources which have been pointed out over the last few years are considered by most authorities to be of minor importance; however, it is felt that they should be mentioned.

It has been proposed that permafrost may exist on the moon and may be a source of water vapor. However, because of the low temperatures at shallow depths below the lunar surface, only small amounts of water vapor would evaporate and escape; thus, contribution to the atmosphere would be negligible.

Because portions of the lunar surface are always shaded, there also exists the possibility that ice may be trapped in these areas. Hinton and Taeusch [13] estimated that the permanently shaded area of the lunar surface is about 0.005 of the total area. With such a small source area available, the amount of gas released into the atmosphere would be insignificant.

Gravitation condensation of interplanetary gas may be an important source, but accurate evaluation must wait until the properties of the solar corpuscular streams and interplanetary gas are better known.

IV. ESCAPE MECHANISMS

Before a lunar atmospheric model can be determined, it is necessary to attempt to establish the escape mechanisms at work on the moon. Some possible escape mechanisms are discussed in the following paragraphs.

A. Thermal Escape

Thermal escape refers to the loss that occurs when molecules reach a velocity greater than the escape velocity of the moon. The temperature and molecular weight of a gas are the governing factors affecting its molecular velocities. Green [20] has determined the sequence of escape of various subliming vapors and gaseous products at a temperature of 400°K representing lunar subsolar temperature and at the temperature of molten lava of 1400°K. In addition, he also has determined the probability of escape of various volcanic gases. The results of his work are presented in Table 7 and Figure 1.

To determine the lifetimes of particles of various gases, Spitzer (cited in Ref. 23) determined the lifetime of particles of gases assuming an isothermal atmosphere. The lifetimes of some of the gases are presented below.

| <u>GASES</u> | <u>LIFETIME</u> |
|----------------|------------------------|
| H ₂ | 1600 sec |
| O ₂ | 1.4 years |
| Xe | 10 ⁴¹ years |
| Kr | 10 ²⁴ years |
| A | 10 ⁸ years |
| Ne | 42 years |
| N | 0.4 years |

The long lifetimes as determined for Xe and Kr show that the relatively small gravitational potential of the moon can cause the heavy gases to remain on the moon for considerable lengths of time, i.e., greater than the estimated age of the moon (4×10^9 years) based on meteoroid frequency and lunar crater count frequency data.

B. Solar Wind Scattering

The loss of atmosphere constituents due to solar wind scattering is an important loss mechanism not only for the light gases, but also for the heavy gases in a strong solar wind regime.

Atoms escape from the atmosphere when the atom, as the result of a collision with a solar wind proton, attains a velocity in excess of the lunar escape velocity. Because of the extremely thin atmosphere, the probability of cumulative collisions is small; therefore, the atom is considered to escape into space or to impact on the lunar surface.

The loss of hydrogen and other light atoms was pointed out by Herring and Licht [14]. Later, Bernstein et al. [15] and Hinton and Taeusch [24] considered the effects of the solar wind on various heavy gases.

Using various solar wind velocities and fluxes, Bernstein et al. [15] calculated the lifetimes of xenon. Using a proton flux of $10^9 \text{ cm}^{-2} \text{ sec}^{-1}$ and wind velocity of $5 \times 10^7 \text{ cm sec}^{-1}$, they computed the lifetime of xenon to be 30 years. Using the same flux rate but with a wind velocity of $2 \times 10^8 \text{ cm sec}^{-1}$, the lifetime of xenon was reduced to one year. Hinton and Taeusch [24] considered the solar wind to be the most important removal mechanism when the solar flux is greater than $10^{11} \text{ cm}^{-2} \text{ sec}^{-1}$. In reaching these conclusions, the lunar magnetic field was considered too weak to be an effective influence.

It can be seen from the preceding discussion that the composition and density of the lunar atmosphere are extensively influenced by the characteristics of the solar wind. Therefore, the characteristics of the lunar atmosphere can be expected to vary with variation in solar activity.

C. Ionic Escape

Ionic escape is considered by Öpik [1] to be the most efficient escape mechanism. Ions escape when the atmosphere acquires a small positive potential through the ejection of photo-electrons into space. The gravity of the ions is neutralized and the ions escape into space.

Hinton and Taeusch [24] considered the rates of photoionizations of argon and neon and the ratio of photoionization and photodissociation of water vapor under three solar wind regimes and concluded that with a weak solar flux ($J = 10^7/\text{cm}^2\text{sec}$ to $10^9/\text{cm}^2\text{sec}$) solar ultraviolet radiation would be the most important escape mechanism.

Because of the ionizing effects of solar ultraviolet radiation, Öpik and Singer [23], considering both a thick and extremely thin atmosphere (thickness less than the free length of path), concluded that the heavy gases such as krypton and xenon would escape the moon. They deduced the escape rates of ions and, using a lunar atmosphere composed of all the krypton and xenon that had evolved from the moon since its creation, they estimated that krypton and xenon ions would have a lifetime of approximately 800 and 50 years, respectively. Through a theoretical treatment of the problem, Öpik and Singer deduced that the moon would have a potential of approximately +120 volts because of solar ultraviolet radiation. Thus, an electrostatic field would exist near the moon. Based on this consideration, krypton and xenon ions would have a lifetime of approximately 1,000 years.

Bernstein et al. [15], using a higher electron temperature than used by Öpik and Singer (275,000°K in lieu of 400°K), concluded that the lunar surface in the presence of the solar wind would not remain positively charged.

The effect of this escape mechanism on the lunar atmosphere cannot be definitely established at this time because of unknowns associated with the problem. However, the results of theoretical studies indicate the need for additional research in this area.

TABLE 7

THERMAL VELOCITIES OF VOLCANIC EMANATIONS AND SUBLIME VAPORS
AT SUBSOLAR AND MOLTEN LAVA TEMPERATURES
(Green, North American Aviation, S&ID 64-1340, p. 46, 1964)

| Volcanic Product | Average Thermal Velocity (V_t) (km/sec) | | Root-Mean-Square Velocity (V_r) (km/sec) | |
|---------------------------------|---|-------------|--|-------------|
| | Subsolar | Molten Lava | Subsolar | Molten Lava |
| | T = 400°K | T = 1400°K | T = 400°K | T = 1400°K |
| Hg ₂ Cl ₂ | 0.13 | 0.25 | 0.15 | 0.27 |
| PbCl ₂ | 0.17 | 0.33 | 0.19 | 0.35 |
| HgCl ₂ | 0.18 | 0.33 | 0.19 | 0.36 |
| Rn | 0.20 | 0.37 | 0.21 | 0.40 |
| Ne | 0.20 | 0.38 | 0.22 | 0.42 |
| As ₂ O ₃ | 0.21 | 0.39 | 0.22 | 0.42 |
| FeCl ₃ | 0.23 | 0.43 | 0.25 | 0.46 |
| Xe | 0.25 | 0.48 | 0.28 | 0.52 |
| SeO ₂ | 0.28 | 0.52 | 0.30 | 0.56 |
| Kr | 0.32 | 0.59 | 0.35 | 0.64 |
| SO ₃ | 0.33 | 0.61 | 0.35 | 0.66 |
| Se | 0.33 | 0.61 | 0.36 | 0.67 |
| As | 0.34 | 0.63 | 0.36 | 0.68 |
| Cl ₂ | 0.35 | 0.64 | 0.38 | 0.70 |
| SO ₂ | 0.36 | 0.68 | 0.39 | 0.74 |
| B(OH) ₃ | 0.37 | 0.69 | 0.40 | 0.75 |
| NaCl | 0.38 | 0.71 | 0.41 | 0.77 |
| NH ₄ Cl | 0.40 | 0.74 | 0.42 | 0.79 |
| CO ₂ | 0.44 | 0.82 | 0.48 | 0.89 |
| Ar | 0.46 | 0.86 | 0.50 | 0.93 |
| HCl | 0.48 | 0.90 | 0.52 | 0.98 |
| H ₂ S | 0.50 | 0.93 | 0.54 | 1.01 |
| S | 0.51 | 0.96 | 0.56 | 1.04 |
| O ₂ | 0.51 | 0.96 | 0.56 | 1.04 |
| N ₂ | 0.55 | 1.03 | 0.60 | 1.12 |
| HF | 0.64 | 1.22 | 0.71 | 1.32 |
| H ₂ O | 0.69 | 1.28 | 0.74 | 1.39 |
| NH ₃ | 0.71 | 1.32 | 0.77 | 1.43 |
| He | 1.45 | 2.72 | 1.58 | 2.95 |
| H | 2.05 | 3.83 | 2.22 | 4.16 |

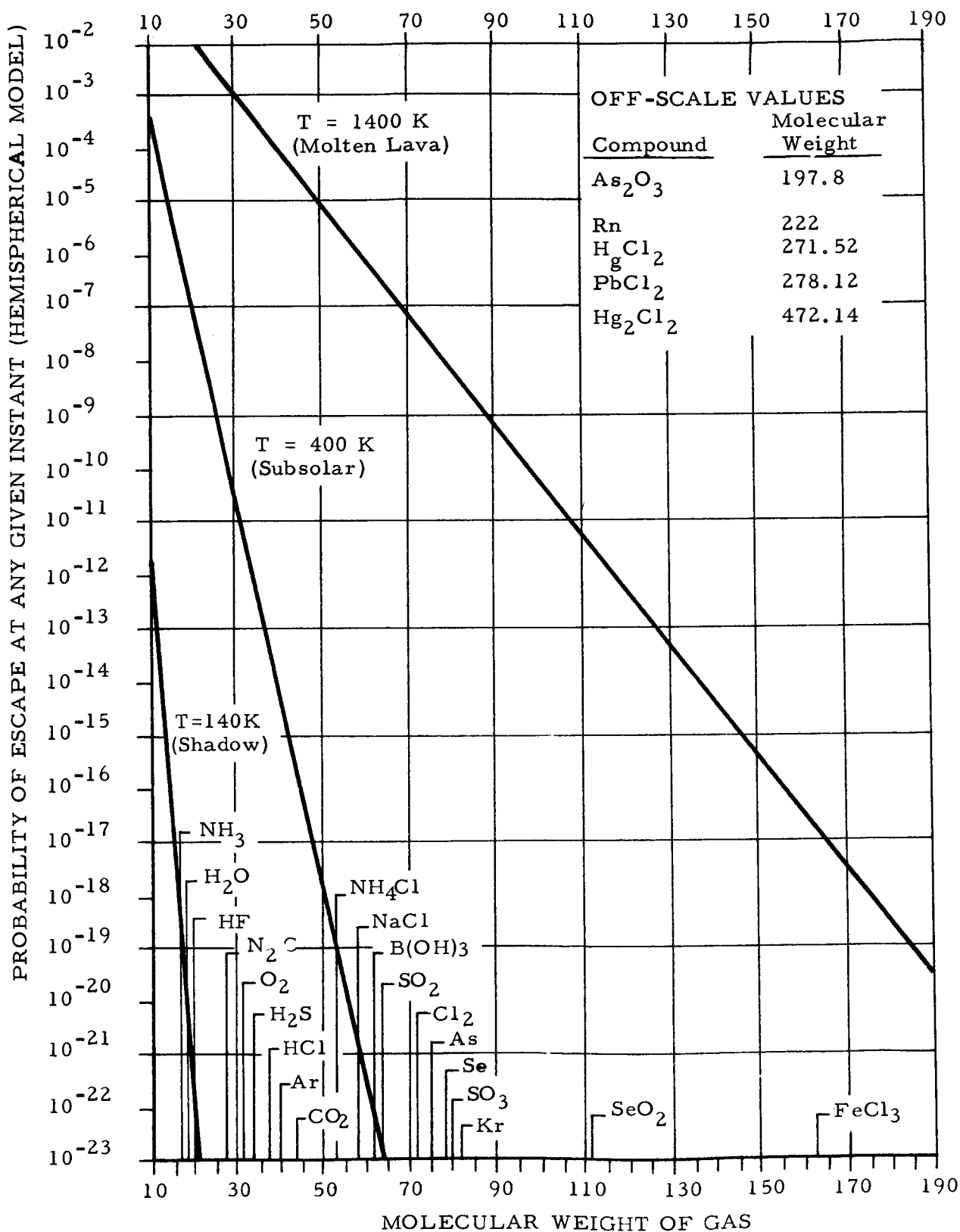


FIGURE 1. PROBABILITY OF ESCAPE DATA FOR VOLCANIC SUBLIMATES (Green, North American Avia., Inc., SID 64-1340, 1964)

V. DEVELOPMENTS OF THE LUNAR ATMOSPHERIC MODEL

In the previous sections we have discussed the various sources which most investigators consider to have produced the lunar atmosphere in its present form. For engineering purposes a lunar atmospheric model must be developed which can represent the expected lunar atmosphere in which various scientific equipment will be expected to operate. Since the lunar atmosphere is in such a continually changing state, a synthetic model should be developed which hopefully can be useful to the designer. The model as synthesized from this literature survey is a combination of the many proposed theoretical and experimentally developed models which have been discussed. Our atmospheric model is as follows:

Engineering Lunar Atmospheric Model (ELAM):

A. Gas Pressure

| | |
|-------------|--|
| Maximum [6] | 10^{-9} times the terrestrial mean sea level pressure |
| Minimum [9] | 10^{-13} times the terrestrial mean sea level pressure |

B. Gas Density

| | |
|-------------|-------------------------------------|
| Maximum [6] | 10^{10} particles/cm ³ |
| Minimum [9] | 10^6 particles/cm ³ |

C. Composition of the Atmosphere Near the Lunar Surface Under Minimum Solar Activity and a Lunar Surface Temperature of 300°K

| (1) <u>Gases [13]</u> | <u>Number of Particles at Surface under Equilibrium Conditions (Particles/cm³)</u> |
|-----------------------|---|
| H | 5.3×10^3 |
| He | 9.13×10^3 |
| H ₂ O | 1.7×10^3 |
| Ar | 5.4×10^4 |
| Kr | 1.7×10^{-2} |
| Xe | 1.87×10^{-3} |

| (2) Charged Particles [13] (Constituents) | Number of Particles at Surface under Equilibrium Conditions (Particles/cm ³) |
|---|--|
| H ⁺ | 3.3 x 10 ⁰ |
| H ⁺⁺ | 5.9 x 10 ⁻² |
| H ₂ O ⁺ | 3.0 x 10 ⁰ |
| Ar ⁺ | 3.41 x 10 ⁻² |

- (3) Other gases such as Ne, CO₂, SO₂, H₂, CO, S₂, and Cl₂ are anticipated; however, their abundance has not been postulated at the present time.

The above atmospheric constituents are based on the minimum solar wind model as presented in Appendix A.

Like all synthetic atmospheric models, this model should be revised on a continuing basis. However, until a better and more realistic model is developed, this model will be considered the design criteria guideline model.

VI. CONCLUSIONS

This report has attempted to review the various lunar atmospheric models and to present an atmospheric model for use as design criteria.

The characteristics of the lunar atmosphere depend on the sources available, the production rates of the sources, and the escape rates of the atoms and ions of the different gases. Because the results of optical and radio observations indicate a very tenuous atmosphere, it is reasonable to conclude that the production rates and escape rates are in equilibrium or that escape rates are dominant. Theoretical approaches indicate that escape rates are dominant. Therefore, the lunar atmosphere is considered to be transitory in nature with a density of less than 10⁻¹³ terrestrial but probably greater than the density of the surrounding interplanetary medium.

The composition of the lunar atmosphere is probably complex and will vary with respect to time and location depending on volcanic, meteoritic and solar activities. The major constituents of a typical lunar atmosphere are probably H₂, H₂O, Ar, He, Kr, and Xe. Minor atmospheric constituents which locally may make up large portions of the atmosphere are SO₂, N₂, CO, S₂, CO₂, and Ne.

Even though some traces of other gases may be present, especially near volcanic emissions, their effect on the characteristics of the atmosphere would be negligible.

The lunar atmosphere and its constituents will be difficult to determine; however, additional work should continue to better define this environmental parameter.

Appendix B

Minimal Model Solar Wind [13]

| | <u>Electrons e</u> | <u>Protons H⁺</u> | <u>Helium Ions He⁺⁺</u> |
|---------------------|--|--|--|
| J (Solar Flux) | $10^9/\text{cm}^2 \text{ sec}$ | $0.93 \times 10^9/\text{cm}^2 \text{ sec}$ | $7 \times 10^7/\text{cm}^2 \text{ sec}$ |
| Ave. Vel. | 500 km/sec | 500 km/sec | 500 km/sec |
| E _{flow} | 0.7 ev = $1.1 \times 10^{-12} \text{ erg}$ | 1300 ev = $2.1 \times 10^{-9} \text{ erg}$ | 5200 ev = $8.3 \times 10^{-9} \text{ erg}$ |
| N | 20/cm ³ | 18.6/cm ³ | 1.4/cm ³ |
| NE* _{flow} | $2.16 \times 10^{-11} \text{ ergs/cm}^3$ | $3.87 \times 10^{-8} \text{ ergs/cm}^3$ | $1.6 \times 10^{-8} \text{ ergs/cm}^3$ |
| T | 10 ⁵ °K | 10 ⁵ °K | 10 ⁵ °K |
| 3KT/2 | 15 ev | 15 ev | 15 ev |

* NE flow is the number density multiplied by the kinetic energy per particle, or the kinetic energy density.

REFERENCES

1. Öpik, E. J., "The Lunar Atmosphere," Planetary and Space Sciences 9, 11, 1962.
2. Green, J., "The Atmosphere of the Moon," Proceedings of Lunar and Planetary Exploration Colloquim, Space and Information Systems Division, North American Aviation, Inc., Downey, Calif., Vol. 3, No. 1, May 1962.
3. Sytinskaya, N. M., The Problem of the Lunar Atmosphere, The Moon, University of Chicago Press, 1962.
4. Jannsen, J., "Comp Rendus de l'academie des sciences de Paris," Vol. 56, 1863.
5. Öpik, E. J., "The Density of the Lunar Atmosphere," Irish Astron., Journ., Vol. 3, No. 5, 1955.
6. Dollfus, A., "Recherche d'une atmosphere autour de la lune," Ann. d'Astrophys, 19, 1956.
7. Elsmore, B., and G. R. Whitfield, "Lunar Occultation of a Radio Star and the Derivation of an Upper Limit for the Density of the Lunar Atmosphere," Nature, Vol. 176, No. 4479, 1955.
8. Bensko, John and R. Q. Shotts, "Lunar Resources," Advances in Space Science and Technology, Vol. 7, 1965.
9. Elsmore, B., "Radio Observations of the Lunar Atmosphere," Phil. Mag. 19, 1957.
10. Hazard, C., M. B. Mackey, and A. J. Shimmins, "Investigations of the Radio Source 3C273 by the Method of Lunar Occultations," Nature, 198, 1963.
11. Rubey, W. W., "Development of the Hydrosphere and Atmosphere," with special reference to "Probable Composition of the Early Atmosphere, Crust of the Earth," ed. by Polderwaard, A.G.S.A. Special Paper 62, 1955.
12. Gold, T., in discussion following R. Jastrow, "Outer Atmosphere of the Earth and Planets," Journal of Geophysical Research, Vol. 64, No. 11, November 1959.
13. Hinton, F. and D. R. Taeusch, "The Lunar Atmosphere," The University of Michigan, Ann Arbor, Michigan, 1962, NASw-133.

REFERENCES (Continued)

14. Herring, J. R. and A. L. Licht, "The Solar Wind," NASA Technical Note D-487, September 1960.
15. Bernstein, W., R. W. Fredricks, J. L. Vogl, and N. A. Fowler, "The Lunar Atmosphere and the Solar Wind," *Icarus*, 2, 1963.
16. Michel, F. C., "Interaction between the Solar Wind and the Lunar Atmosphere," *Planet and Space Science*, Vol. 12, 1964.
17. Vestine, E. H., "Evolution and Nature of the Lunar Atmosphere," *Proceedings of Lunar and Planetary Exploration Colloquium*, Vol. 1, No. 1, May 1958.
18. Shepherd, E. S., "The Gases in Rocks and Some Related Problems," *American Journal of Science*, Vol. 35A, 1938.
19. Green, J., "Geochemical Aspects of Lunar Degassing," *Proceedings of Lunar and Planetary Exploration Colloquium*, Space and Information Systems Division, North American Aviation, Inc., Downey, Calif., Vol. 1, No. 4, January 1959.
20. Green, Jack, "Tidal and Gravity Effects Intensifying Lunar Defluidization and Volcanism," *Space and Information Systems Division*, North American Aviation, Inc., Downey, Calif., August 1964.
21. Eaton, J. P. and K. J. Murata, "How Volcanoes Grow," *Science*, Vol. 132, No. 3432, October 1960.
22. Mazor E. and G. J. Wasserburg, "Helium, Neon, Argon, Krypton, and Xenon in Gas Emanations from Yellowstone and Lassen Volcanic National Parks," *Geochimica et Cosmochimica Acta*, Vol. 29, 1965.
23. Öpik, E. J. and S. F. Singer, "Escape of Gases from the Moon," *J. Geophys. Res.*, 65, 1960.
24. Hinton, F. L. and D. R. Taeusch, "Variation of the Lunar Atmosphere with the Strength of the Solar Wind," *J. of Geophys. Research*, Vol. 69, No. 7, April 1964.
25. Jaggar, T. A., "Magmatic Gases," *American Journal of Science*, Vol. 238, No. 5, May 1940.
26. Naughton, J. J., K. Terada, "Effects of Eruption of Hawaiian Volcanoes on the Composition and Carbon Isotope Content of Associated Volcanic and Fumarolic Gases," *Science*, Vol. 120, October 1954.

BIBLIOGRAPHY

- Allen, E. T., "Chemical Aspects of Volcanism with a Collection of the Analyses of Volcanic Gases," Franklin Institute Journal, Vol. 193, 1922.
- Aronwitz, L. and S. N. Milford, "Magnetic Shielding of the Lunar Surface from the Solar Wind as a Function of Lunar Magnetic Moment," Journal of Geophysical Research, Vol. 70, No. 1, 1965.
- Baadsgaard, H., J. Lipson and R. E. Folinsbee, "The Leakage of Radiogenic Argon from Sanidine," Geochimica et Cosmochimica Acta., Vol. 25, 1961.
- Brandt, J. C., "Density of the Lunar Atmosphere," Science 131, 1960.
- Briggs, M. H., "The Chemistry of the Lunar Surface," British Interplanetary Society Journal, Vol. 18, July-August 1962.
- Cameron, A. G. W., "The Origin of the Atmosphere of Venus and the Earth," Icarus, Vol. 2, No. 3, October 1963.
- Dollfus, A., "A New Investigation of an Atmosphere in the Neighborhood of the Moon," Comptes Rendus, 234, 1952.
- Elsmore, B. H. and C. van de Hulst, ed., "The Lunar Occultation of a Radio Star and the Derivation of an Upper Limit for the Density of a Lunar Atmosphere," Radio Astronomy, Cambridge Univ. Press, London, 1957.
- Edwards, W. F. and L. B. Borst, "Possible Sources of a Lunar Atmosphere Science," 127, 1958.
- Ellis, A. J., "Chemical Equilibrium in Magmatic Cases," American Journal of Science, Vol. 255, June, 1957.
- Fabry, C., "Leroledes Atmospheres dans les Occultations par les Planetes," Journal des Obserateurs, Vol. 12, No. 1, 1929.
- Fesenkov, V. G., "Omasse Lunnay Atmosfery," DKlady Akad Nauk, SSSR, Vol. 39, 1943.
- Firsoff, V. A., "Dissipation of Planetary Atmospheres," Science, Vol. 130, 1959.
- Firsoff, V. A., "Density of the Lunar Atmosphere," Science, Vol. 131, 1959.
- Gould, R. J., "Hydrogen Near the Moon," Center for Radiophysics and Space Research, Cornell University, Ithaca, New York, April 1962.

BIBLIOGRAPHY (Continued)

Herring, J. R. and A. L. Licht, "Effect of the Solar Wind on the Lunar Atmosphere," Science, Vol. 30, 1959.

Herring, J. and L. Kyle, "Density in a Planetary Exosphere," J. Geophys. Res., Vol. 66, 1961.

Herzberg, G., Popular Astronomy, Vol. 54, 1946.

Hoyle, F., and W. A. Fowler, "On the Abundance of Uranium and Thorium in Solar System Material," Isotopic and Cosmic Chemistry, H. Craig, S. Miller and G. J. Wasserburg, eds., North Holland Publ. Co., Amsterdam, 1963.

Jeans, J. H., The Dynamical Theory of Gases, Dover, N. Y., 1954

Keyper, D., "Obzar Atmosfer Planet," Sls. Atmosfery Zembi, planet, 341 Izdvo inostr. literatury, 1951.

Kozyrev, N. A., "Lyuminestsentsiya Lunnoy Poverkhnosti i Intensivnost' korpuskulyarnogo islucheniya Solntsa," Izv. Krymskoy astrof. observ., Vol. 16, 1956.

Miyamoto, S., "Morphological Aspects of the Lunar Crust," Icarus, Vol. 3, 1964.

Nakada, M. P. and J. D. Mihalow, "Accretion of Solar Wind to Form a Lunar Atmosphere," J. Geophys. Res., 67, 1962.

Niedz, F. J., "Survey of the Physical and Environmental Parameters of the Moon," Apollo Support Department, General Electric Company, Daytona Beach, Florida, February 1963, NASw-410-20-1310.

Öpik, E. J., and S. F. Singer, "Distribution of Density in a Planetary Exosphere," Phys. Fluids, Vol. 2, 1959.

Öpik, E. J. and S. F. Singer, "Distribution of Density in a Planetary Exosphere," Phys. Fluids, Vol. 3, 1960.

Rittmann, A., Volcanoes and Their Activity, New York and London, John Wiley and Sons, 1962.

Rogers, J. R. and O. H. Vaughan, "An Interpretation of the Surface of the Moon and Its Atmosphere," NASA TM X-53124, September 1964, Unclassified.

Salisbury, J. W. and P. E. Glaser, ed., "Studies of the Characteristics of Probable Lunar Surface Materials," AFCRL-64-970, January 1964.

BIBLIOGRAPHY (Continued)

Singer, S. F., "Atmosphere Near the Moon," *Astronautica Acta*, Vol. 7, 1961.

Smith, R. E., ed., "Space Environment Criteria Guidelines for Use in Space Vehicle Development," NASA TM X-53142, September 1964, Unclassified.

Spitzer, L., Jr., "The Terrestrial Atmosphere above 300 Km," The Atmospheres of the Earth and Planets, University of Chicago Press, Chicago, Illinois, 1952.

Stanley, James T. and Wilmuth C. Lucas, "A Survey of Scientific Experiments and Investigations for AES Shelter-Roving Vehicle Mission in Exploration of the Moon," Northrop Space Laboratories, NAS8-11096, April 1965.

Vestine, E. H., Rand Corporation Research Memorandum, RM-2106, 1958.

Wehner, G. K., "Sputtering Effects on the Moon's Surface," *ARS Journal*, March 1960.

Wehner, G. K., J. E. KenKnight, and D. Rosenberg, "Modification of the Lunar Surface by the Solar Wind Bombardment," *Planet and Space Science*, Vol. II, 1963.

Wehner, G. K., D. L. Rosenberg, and J. E. KenKnight, "Sputtering Effects on the Moon's Surface," General Mills Electronics Group, Minneapolis, Minn., NASw-424, October 1962.

Wehner, G. K., D. L. Rosenberg, and J. E. KenKnight, "Investigation of Sputtering Effects on the Moon's Surface," General Mills Electronics Division, Minneapolis, Minn., July 31, 1963.

Weil, Herschel and M. L. Barasch, "A Theoretical Lunar Ionsphere," *Icarus*, Vol. 1, 1963.

Weissler, G., "Photoionization in Gases and Photoelectron Emission from Solids," Handbuch der Physik, Bd. XXI, p. 304 Springer-Verlag, Berlin, 1956.

APPROVAL

THE LUNAR ATMOSPHERE

by

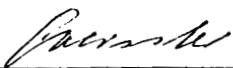
Wilmuth C. Lucas and Otha H. Vaughan, Jr.

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.



W. W. Vaughan
Chief, Aerospace Environment Office



E. D. Geissler
Director, Aero-Astrodynamics Laboratory

DISTRIBUTION LIST

INTERNAL

| | |
|----------------|----------|
| DIR | MS-T (6) |
| DEP-T | CC-P |
| R-DIR | MS-H |
| R-AS-DIR (4) | |
| R-AERO-DIR | |
| R-AERO-Y (40) | |
| R-AERO-S (5) | |
| R-AERO-T (2) | |
| R-AERO-A (2) | |
| R-AERO-DP (2) | |
| R-ASTR-DIR (3) | |
| R-ASTR-A (5) | |
| R-P&VE-DIR (3) | |
| R-P&VE-A (4) | |
| R-P&VE-AB (5) | |
| R-P&VE-AL (5) | |
| R-RP-DIR (3) | |
| R-RP-J (5) | |
| R-QUAL-DIR | |
| R-COMP-DIR (3) | |
| R-ME-DIR (3) | |
| R-TEST-DIR (3) | |
| I-DIR (4) | |
| MS-IP | |
| MS-IL | |

EXTERNAL

Mr. William Elam (2)
Bellcomm, Inc.
1100 17th St. N. W.
Washington, D. C.

Dr. Alex E. S. Green
University of Florida
Physics Department
Gainesville, Florida

Dr. Seymour L. Hess
Florida State University
Department of Meteorology
Tallahassee, Florida

DISTRIBUTION (Continued)

EXTERNAL (Cont'd)

U. S. Geologic Survey
Branch of Astrogeology
Box 1906
Flagstaff, Arizona 86002
Attn: Dr. D. Elston
Dr. J. McCauley
Dr. L. Rowen

Commander
Headquarters, Air Weather Service
Scott Air Force Base, Illinois

Commander
Air Force Systems Command
Andrews Air Force Base
Washington, D. C.

NASA-Langley Research Center
Langley Field, Virginia
Attn: Dr. F. L. Thompson, Dir.
Mr. R. Hord
Mr. T. Coleman
Library (5)

NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771
Attn: Dr. J. Clark, Dir.
Mr. D. C. Kennard, Jr.
Dr. J. O'Keefe
Library (5)

Director
Office of Manned Space Flight
NASA Headquarters
Washington, D. C. 20546
Attn: Dr. George Mueller, Dir.
Mr. P. E. Culberson - MTL
Mr. Bart Campbell
Mr. D. Beattie
Mr. E. Andrews

Office of Advanced Research and
Technology
NASA Headquarters
Washington, D. C. 20546
Attn: Mr. M. Charak
Mr. M. B. Ames
Mr. R. Rhode
Mr. D. Gilstad
Mr. D. Michel

Office of Space Science and Appli-
cations
NASA Headquarters
Washington, D. C. 20546
Attn: Dr. Homer Newell, Dir. (2)
Dr. Willis B. Foster (2)
Dr. R. F. Fellows
Mr. Robert P. Bryson
Dr. R. Allenby
Dr. Peter Badgley

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena 3, California 91103
Attn: Mr. Conway Sydnor
Dr. R. Meghrebian
Dr. T. Urebalovich
Tech Library (5)

NASA-Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135
Attn: Dr. Abe Silverstein, Dir.
Library (4)

DISTRIBUTION (Continued)

EXTERNAL (Cont'd)

NASA-Ames Research Center
Moffett Field
Mountain View, California 94035
Attn: Director
Library (5)

NASA-Manned Spacecraft Center
Houston, Texas 77001
Attn: Dr. R. R. Gilruth, Dir.
Dr. Joseph Shea
Mr. Christopher Craft
Mr. Donald K. Slayton
Mr. John Dornbach (3)
Mr. John Harris (3)
Tech Library (2)

Scientific and Technical Information Facility (25)
Attn: NASA Representative (S-AK/RKT)
P. O. Box 5700
Bethesda, Md.

Air Force Cambridge Research Laboratories
Bedford, Mass.
Attn: CRFL, Dr. J. W. Salisbury (2)
Tech Library (5)